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Experiences with the Muon Alignment Systems of the Compact Muon Solenoid Detector

Noemi Beni on behalf of CMS experiment[1]

Institute of Nuclear Research of the Hungarian Academy of Sciences
Debrecen, H-4026, Hungary

Abstract

After briefly explaining the need for a precise muon chamber alignment, the different muon alignment systems implemented at CMS are described. Due to the tight spatial confinement and challenging large radiation and high magnetic field environment, unique alignment systems had to be developed that handle separately the Barrel and the Endcap regions. A third subsystem, called Link, connects these two together and to the Tracker in a common reference frame. The aligned chamber geometry obtained from the Hardware-based muon alignment is validated by comparisons with photogrammetry information and by studies of residuals of muon tracks extrapolated between chambers. Stability studies, for which the hardware systems are particularly well suited, are also discussed.

Alignment methods based on tracks are also described. Muons from cosmic rays and from collisions are used to align the chambers relative to the inner tracker. In addition, beam halo muon tracks traversing overlapping endcap chambers are used for internal endcap alignment. A comparison between the track-based and hardware-based results is given, together with an explanation of the advantages and disadvantages of the different alignment strategies.

Keywords: CERN, LHC, CMS, Muon detector, Alignment

1. Introduction

The Compact Muon Solenoid (CMS) [1] is a general purpose detector at the Large Hadron Collider (LHC) accelerator at CERN. The weight of detector is about 12500 tons, its diameter is about 14 meters and it is about 20 meters long. It is composed of 5 wheels (Yoke Barrel, YBs) and 3+3 endcap disks (Yoke Endcap, YEs). The CMS Muon System [2] uses three types of muon detectors. There are 250 Drift Tube (DT) muon chambers in the barrel region (DTs are organized into 4 concentric stations called MB1 through MB4) and 468 Cathode Strip Chambers (CSC) in the endcap region. Resistive Plate Chambers (RPC) are in both regions, in the close vicinity of the DTs and CSCs. They play a major role in the Muon Trigger System.

[1]Email: Noemi.Beni@cern.ch

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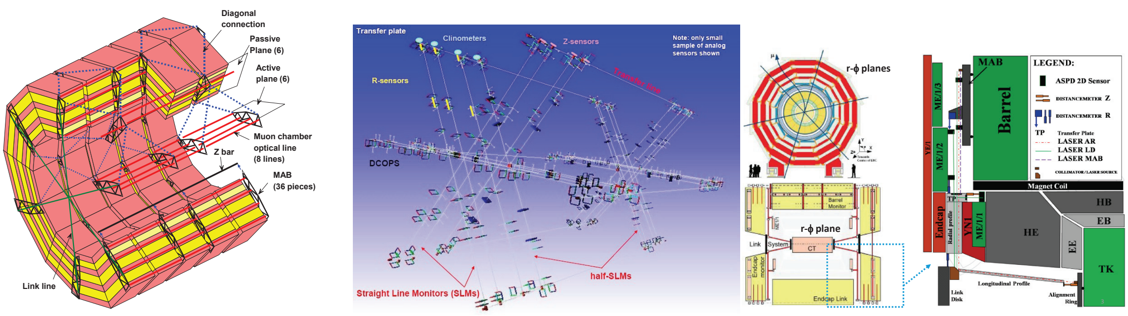
2. CMS Muon Alignment Systems

2.1. Motivation for the Muon Alignment System

Precise measurement of muons up to the TeV/c momentum range requires the DTs and CSCs to be aligned with respect to each other, and to the central tracking system, with an accuracy of a few hundred microns, comparable to their intrinsic spatial resolution [3]. CMS has a 3.8T superconducting solenoid magnet. The strong magnetic forces created by its magnet can displace, rotate and deform the heavy yoke elements by several millimeters. These iron yokes are furthermore distorted by gravity. The yokes are movable, and the expected position reproducibility for such large and heavy structures is at the mm level at best. Moreover, thermal instability effects might contribute at the sub-mm level. The Muon Alignment System must track these effects after CMS is closed and the magnet is switched on. The system has to tolerate large magnetic fields and radiation exposure.

The alignment positions and orientations are used as corrections by the CMS reconstruction software and the system provides absolute positions and orientations of chambers in the frame of reference defined by the central Tracker. Of course the system is also able to follow relative changes.



(a) (b) (c)

Fig. 1: Schematic view of the three hardware alignment systems (a) Barrel (b) Endcap (c) Link

2.2. Barrel Alignment System

The goal of the Barrel Alignment System [3, 4] is to align the 250 DT chambers with respect to each other in a common frame. The system consists of a redundant optomechanical network of 10000 LEDs mounted on DT chambers and ~600 video cameras installed on 36 rigid carbon fibre structures called MABs (Module of the Alignment of Barrel). The schematic view of this optomechanical network can be seen in Figure 1a. Each MAB has one Board Computer that handles the read-out of the cameras and controls some of the light sources. The MABs are attached to the Barrel Yoke in such a way that they cannot pick up deformations from the iron yoke. In addition to the above mentioned Barrel devices, active MABs (MABs in active planes, show in Figure 1a) contain Endcap Alignment components MABs attached to wheels ±2 contain Link and Endcap components. Carbon fiber rods equipped with LEDs (Z-bars) are attached to the vacuum tank of the solenoid and read by the active MABs in order to provide a better Z-resolution.

2.3. Endcap Alignment System

The Endcap Alignment System [3, 4] aligns the CSC chambers with respect to each other and measures the bending and the relative Z position of the yoke endcaps. This system is a network of optical connections complemented by clinometers, axial and radial distance meters. The bending measurement of yoke endcaps is done by the Straight Line Monitors (SLM). There are three nearly radial SLM lines per Muon Endcap (ME) station. These laser lines are read by Digital CCU Optical Position Sensors (DCOPS). Each SLM measures only 4 chambers, therefore the Endcap System measures only about the 1/6 of all the CSCs. The relative Z distance between ME stations is measured by Z-sensors. Additional SLM lines called Transfer Lines running along the CMS axial Z direction measure relative X, Y displacements between ME stations. The laser network of the system seen in Figure 1b.

2.4. Link Alignment System

The Link Alignment System [3, 4] monitors DTs and CSCs in a common frame of reference related to the Tracker through a network of optical connections which can be seen in Figure 1c. It uses laser sources housed in rigid structures. These are the Alignment Rings (AR) attached to the tracker, the Link Disks (LD) mounted on Yoke Endcaps YE±1 and the MABs on the Barrel wheels. These lasers are read by optical 2D sensor called Amorphous Silicon-strip Position Detectors (ASPD) mounted on the Muon Endcap (ME±1) chambers and on the MABs on the Yoke Barrel (YB±2). The Link Alignment System is organized into three $r\phi$ planes staggered 60° in ϕ (to match the YB 12-fold geometry). Each plane consists of four independent quadrants for a total of 12 Link quadrants (6 on each CMS Z-side).

2.5. Calibration/Installation/Commissioning and Operation

The calibration of elements of the Hardware Muon Alignment System started after 2002. The Installation and Commissioning of the full system started in 2003. For the CMS Magnet test (in 2006) a partial Muon Alignment System was built in order to test its feasibility. The full system was ready by 2008. There were challenges during the installation of the system. There was only limited space available for cables and hardware elements, due to a tight spatial confinement. To clean away the light blocking objects (cables, pipes, covers) before the closure of the detector was very important. The LDs and ARs are very close to the fragile Beam Pipe, therefore extreme care was needed during the installation of these elements. Alignment elements are trapped between the wheels, blocking access to most of the system after CMS has been closed. The three subsystems need different time-intervals to measure one full cycle. The Barrel Alignment needs $\sim$2 hours, while the Link Alignment measurement cycle is $\sim$30 mins and the Endcap Alignment needs $\sim$15 mins to measure one full cycle. Therefore the full time granularity of the Muon Alignment System is driven by the Barrel Alignment. The operation of the system has been integrated into the CMS Detector Control System (DCS) and all the three alignment systems have common LV control.

2.6. Track-based Alignment

Track-based Alignment measures precisely the muon chamber positions with respect to the Tracker. It relies on precise reconstruction of muon tracks in the inner silicon tracker. Tracks from the ”reference” tracker are propagated to the ”target” muon system. The differences between propagated trajectory and muon chamber hits or segments (residuals) are calculated in each chamber and used for corrections. The track-based Alignment uses muon tracks from all recorded collisions data.

3. Offline data analysis

3.1. Barrel Alignment System

The Offline analysis chain of the Barrel System is described on the chart flow in Figure 2. A dedicated reconstruction software called CMS Object-oriented Code for Optical Alignment (COCOA) [6] is used to transform the various optical measurements into a reconstructed DT aligned geometry. This geometrical reconstruction is based on iterative non-linear χ^2 fit. This system is unable tolerate bad measurements, therefore a careful check of each measurement data and exclusion of bad measurements are needed before the start of the reconstruction. This task is done by the Data Quality Assurance (DQA) program. The DQA does -among other things- fast pattern checks on the measured data in order to exclude reflections of the light sources.

During the first step the position and orientation of MABs and MB1-2-3 stations are calculated, defining the barrel in a floating coordinate system. Station 4 chambers are added in a second step in order to simplify significantly the computational problem and to run the reconstruction much faster. Another reason for this factorization is that the calibration of camera positions on MABs for the outer station is less precise than

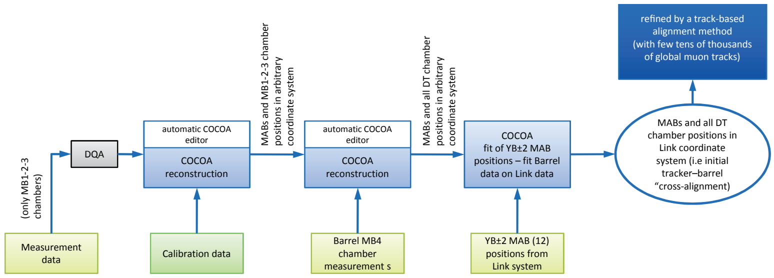
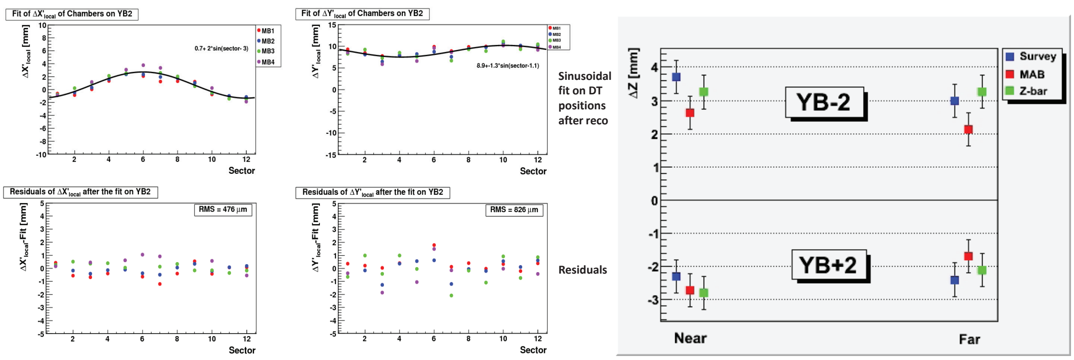


Fig. 2: The offline analysis chain of the Barrel Alignment System

that for the internal barrel, therefore the structure is essentially not affected by excluding station 4. The overwhelming part of these steps are automatized (specially the measured and calibration data retrieval from the database) and the plan is to make the reconstruction fully automatic. In the final step, the resulting rigid, floating barrel structure is positioned (and oriented) in space by fitting the MABs in YB±2 to the positions obtained by the Link System for the same MABs. At this point the MABs and the DT positions are transformed into the Link Alignment coordinate system which is the initial tracker-barrel cross-alignment. This cross-alignment is further refined by a Track-based Alignment method which uses internally aligned Tracker and Muon Barrel Systems and obtains their relative position and orientation using only a few tens of thousands of global muon tracks.

3.1.1. Comparison with Survey measurements



(a) (b)

Fig. 3: Barrel Alignment comparison with the Survey results. (a) The comparison of Barrel Alignment and Photogrammetry measuements results on DT chambers before (top) and after (bottom) correcting for the relative overall wheel movement (b) Comparison of Survey measurement with Z-bar and reconstructed MAB position results

The comparison of the Barrel Alignment results to the Survey measurements is a good way to validate the system. Two comparisons were done: the first one is the comparison with photogrammetry. Care must be taken since the photogrammetry measurement was done at 0T with an open detector, while the alignment measurement was done after detector closure. During closure the wheels can move and tilt a bit, and since the same MABs are used to measure barrel chambers sitting on different wheels, only the relative positions of the DTs within each wheel can be expected to agree. Therefore all comparisons are made independently for each wheel. Large disagreements between photogrammetry and alignment are expected to show clear trends which is an evidence for an overall wheel movement between the two sets of measurements. After correcting for the wheel movement with a sinusoidal fit on chamber positions, the internal wheel structures can be compared. These plots are shown in Figure 3a. The average agreement in $r\phi$ ($\Delta X'_{local}$) and z ($\Delta Y'_{local}$) for the chambers are quite good after factorizing out collective wheel movements.

The second is the comparison of mutually independent Z measurement of the Barrel wheels (YB±2). Together with the CERN Survey group some survey measurement points were measured at 0T and at 3.8T in order to measure the Z position change of the barrel wheels. Both the barrel and the survey measurements were done at the same time in January and February of 2011. The comparison of the Z-contraction calculated from the survey data and from the Barrel Alignment measurements can be seen in Figure 3b. There are two independent measurements from the Barrel Alignment: one is the Z-bar measurements and the other is the reconstructed MAB position data. As we can see in the plot, the Z-bars and MABs are very much compatible with Survey. The errors of the different measurements are ±0.5 mm for the Survey measurements, $\pm 800\text{x}\,\sqrt{2}/\sqrt{6} \sim \pm 0.5$ mm in case of the reconstructed MABs and $\sim \pm 0.5$ mm for the Z-bar measurements.

3.1.2. Results on the detector deformations

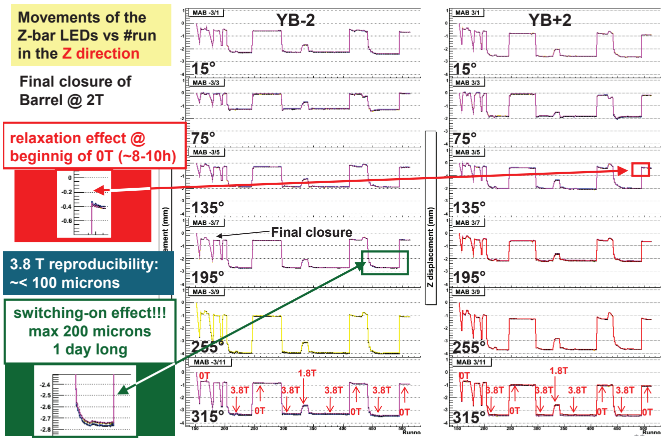


Fig. 4: Wheel movements in magnetic field measured by Z-bar system

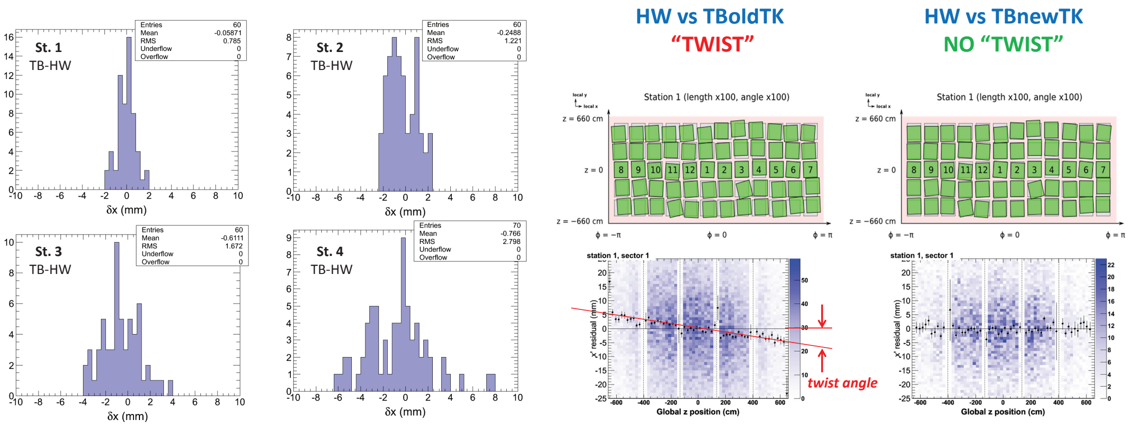
The detector behavior in magnetic field can be estimated from the Z-bar measurement data. From the movement of the Z-bar light sources three effects were observed: the final closure of the barrel wheels at 2T magnetic field, magnet switch-on effects at the end of the magnet ramp-up to 3.8T, when a one day long movement of the wheels by 200 microns is observed, and a 8-10 hours relaxation effect at the end of magnet ramp-down. Plots illustrating these effects are shown in Figure 4.

3.1.3. Comparison of the results of the track-based and the hardware-based Barrel Alignment methods

The comparison of track-based and hardware based alignments is an important cross-check of the muon barrel alignment system at 3.8T. The track-based alignment used 35 pb^{-1} of data recorded from collisions in 2010. The muon p_T range used is from 20 GeV to 200 GeV. The results of the comparison can be seen in Figure 5a. As one can see the RMSs is consistent with the expectations: it grows with the radius from the beam pipe, from ~1 mm for the inner stations to ~2-4 mm for the outer stations.

3.1.4. Twist lesson

A relative "twist" was observed in 2010 in the barrel in track-based muon alignment with respect to the hardware muon alignment, visualized in Figure 5b. This was an overall 4-5 mm end-to-end difference both in Z and $r\phi$. Many studies were performed by the community in order to find the reason. Results of these studies showed that the three hardware alignment system are consistent with each other and with the



(a) (b)

Fig. 5: (a) Track-based and hardware-based alignment comparison for each chamber station in the barrel region. (b) Plots visualizing the "twist" problem.

Survey measurements at 0T. However, at 3.8T photogrammetry measurement was impossible to perform on the system. The solution came from physics in the form of a bias in the Z mass as a function of Z. It turned out that the Tracker track-based alignment has a weak mode which, if taken into account, the "twist" goes away. The lesson is that comparisons of track-based and hardware muon alignments can be a handle to deal with possible tracker deformations or alignment weak modes, and an independent hardware measurement is needed. The hardware muon alignment plans a special upgrade to better deal with this issue.

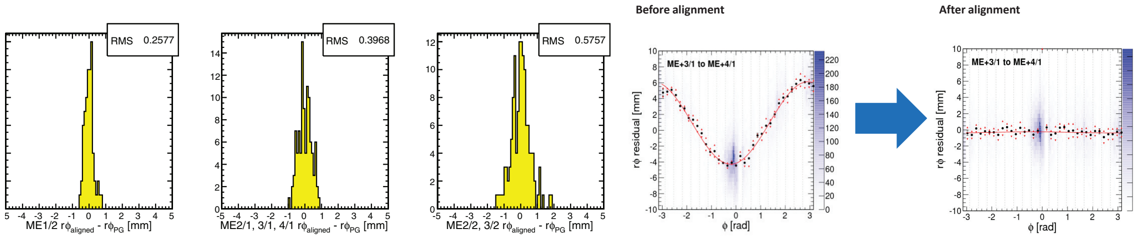
3.2. *Endcap Alignment System*

The muon endcap was aligned using information from 4 different sources: photogrammetry, the combined information from Encap and Link Alignment System, tracks from beam-halo muons, and tracks from collision muons. Some of these sources measure the same alignment parameters in different ways and providing cross-checks between the different systems, while others don't. To combine the information, alignment corrections were applied in a well-defined sequence, such that each step benefited from the previous. Potentially interdependent corrections were iterated to obtain a mutually consistent solution.

Photogrammetry measurement was done on the endcap chambers at 0T when the yoke elements were open. From this measurement the ring alignment at 0T can be extracted, that is the alignment of CSCs in one disk with respect to each other. The endcap disks suffer deformation when the solenoid is switched on. The CSC chambers follow the deformation of the endcap disks and therefore some of them can move towards the center of the detector by as much as 14 mm, as well as rotate around their local X-axis by as much as 3.5 mrad. The hardware alignment system measures these deformations and the Z position of the yoke elements at 0T and 3.8T.

CSC chambers in CMS are designed with a small overlap region along their edges. Muons passing through these narrow regions provide information about the relative displacement of the neighboring chambers. The ring alignment at 3.8T can therefore be done using beam-halo muons. Although photogrammetry information was used to constrain a fraction of the chambers, much larger weights were given to the beam-halo data, in inverse proportion to the square of the measurement uncertainties in the two methods. As seen in Figure 6a, the level of agreement between the track-based technique and photogrammetry is 0.3-0.6 mm. This is much smaller than the typical scale of chamber corrections from design geometry (2-3 mm).

To complete the endcap alignment, the internally aligned rings must be aligned relative to one another and the Tracker. Tracks from the Tracker are propagated to the muon chambers and whole-ring corrections are derived from the pattern of $r\phi$ residuals as a function of global ϕ. A constant offset in the residuals

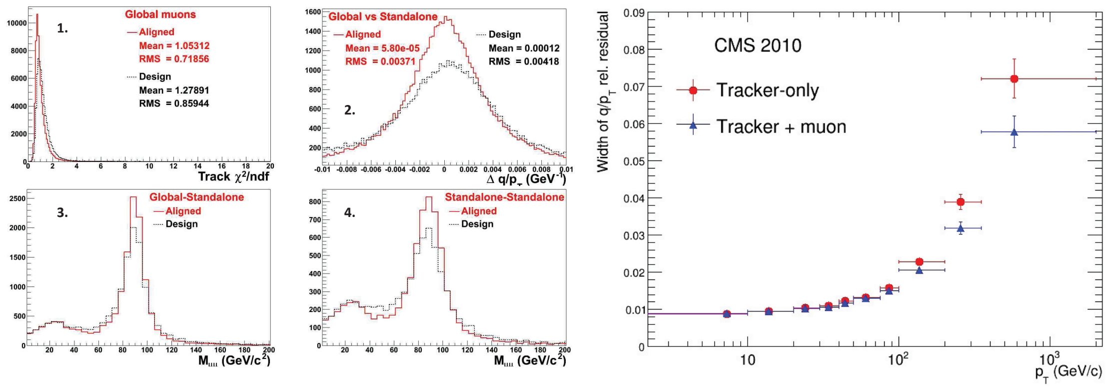


(a) (b)

Fig. 6: (a) Chamber positions after internal-ring alignment compared with photogrammetry, split by ring (ME1/1 chambers were not measured by the photogrammetry) (b) Residuals from beam-halo tracks are used to cross-check the alignment performed with collisions. Left: before alignment. Right: after alignment using collisions (not beam-halo)

is interpreted as a rotation of the ring in ϕ, while terms proportional to $cos\phi$ and $sin\phi$ are interpreted as displacements in global x and y, respectively. To cross-check the alignment using a qualitatively different method, beam-halo tracks crossing an entire endcap (3 or 4 stations, depending on distance from the beamline) are used to calculate residuals by extrapolating segments from one station to another. Figure 6b shows an example, in which ME+3/1 segments were propagated linearly (no corrections for material or magnetic field) to ME+4/1. These plots were not used to perform the alignment, so the fact that the strong ϕ trend observed before alignment is eliminated in the aligned geometry adds confidence to the result.

4. Alignment impact on Physics



(a) (b)

Fig. 7: Alignment impact on physics data. (a) Distributions of muon-related quantities for low momentum muons (b) Gaussian width of the difference in q/p_T between top and bottom reconstructed cosmics using aligned muon chamber positions compared to Tracker-only reconstruction

The most important test for any calibration or alignment is to study its effect on the reconstructed quantities. In the case of muon alignment, higher-level objects related to muon tracks must be studied. It is important to keep in mind that, by design, the momentum resolution is dominated by the central tracker for muons with transverse momentum below 200 GeV/c. A well-aligned muon system is therefore expected to induce minor beneficial changes at reconstruction level for low momentum global muons, and to improve global muon measurements for very energetic muons. Plots on Figure 7a show distributions of the muon-related quantities for low momentum muon tracks from pp collisions collected during 2010. The solid red and dotted black distributions correspond to the aligned and design (no alignment corrections ie. unaligned chambers left at nominal positions), muon chamber geometries respectively. The plot marked with 1 shows the improvements of χ^2 for global tracks. Plot 2 shows the difference in q/p_T between muons reconstructed as global and as stand alone. Plots 3 and 4 show the improvement in di-muon mass resolution in the Z^0 region when at least one muon is reconstructed as Stand Alone (using muon chambers only).

In order to study the effect of the alignment on highly energetic muons, cosmic ray muons must be used since currently there are very few high momentum muon tracks (above 200 GeV/c) available from pp collisions. The Gaussian width of the difference in q/p_T between top and bottom reconstructed cosmics using aligned muon chamber positions compared to Tracker-only reconstruction (Figure 7b). As expected the aligned muon system improves tracker-only p_T measurements above 100 GeV/c.

5. Summary

The three hardware Alignment Systems show good agreement with each other and with the Survey measurements. Agreement between the independent hardware and track-based alignments is consistent with current track-based statistical precision. The CMS Muon Alignment System has an impact on physics: it improves track reconstruction (χ^2) and improves μ-μ mass reconstruction for low p_T stand alone muons. The System improves momentum resolution for muons above 100 GeV/c. Work is ongoing on alignment using stand alone muons and on the determination of Alignment Position Errors (APE) for all chambers. And the hardware Barrel Alignment System has an upgrade plan for the Long Shutdown in 2013.

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